Indirect aerosol forcing

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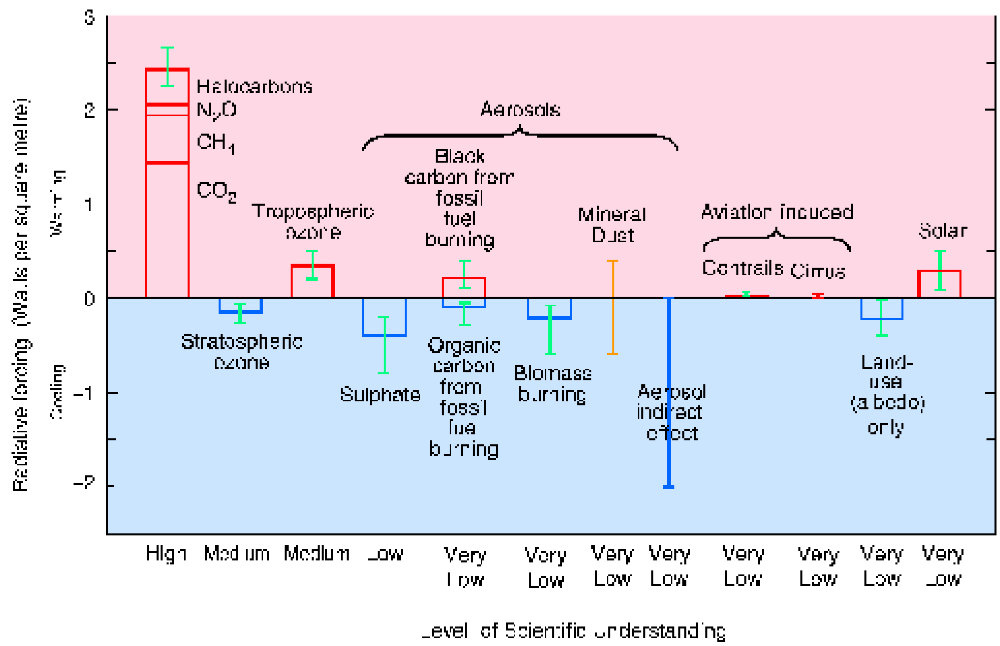
Global-mean radiative forcing 1750–2000



- Highly uncertain, but possibly (probably) substantial
- Composition specificity?
- Spatial variation?

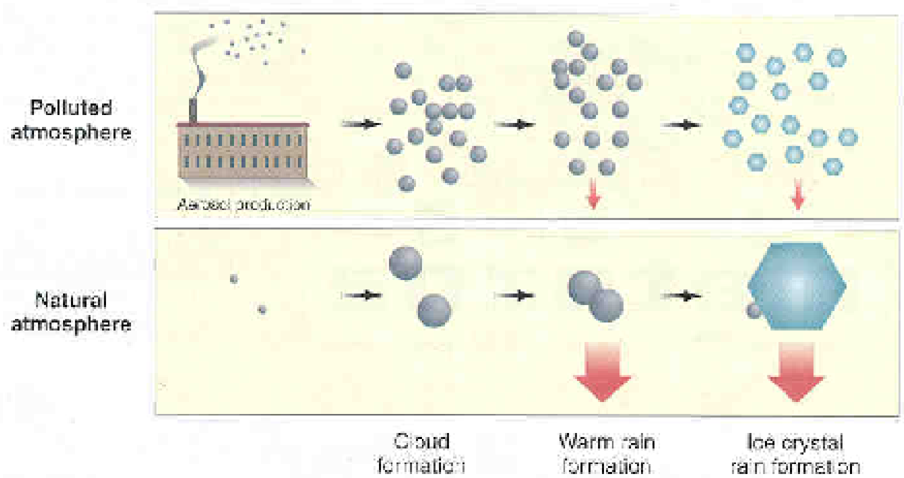
First indirect aerosol effect

Polluted airmass has more aerosols, hence more cloud droplets.

- Cloud albedo depends on droplet surface area, so second cloud is brighter ("Twomey effect", or "first indirect effect").
- Quantified by effective radius R_{eff}.
- Lots of evidence to support this effect.

Second indirect aerosol effect

Suppression of precipitation in polluted clouds.



- “Cloud lifetime” or “second indirect” effect
- Much less evidence for this one.

Observational evidence: Ship tracks

"Textbook" example of indirect aerosol effect (e.g., Coakley et al., Science, 1987).

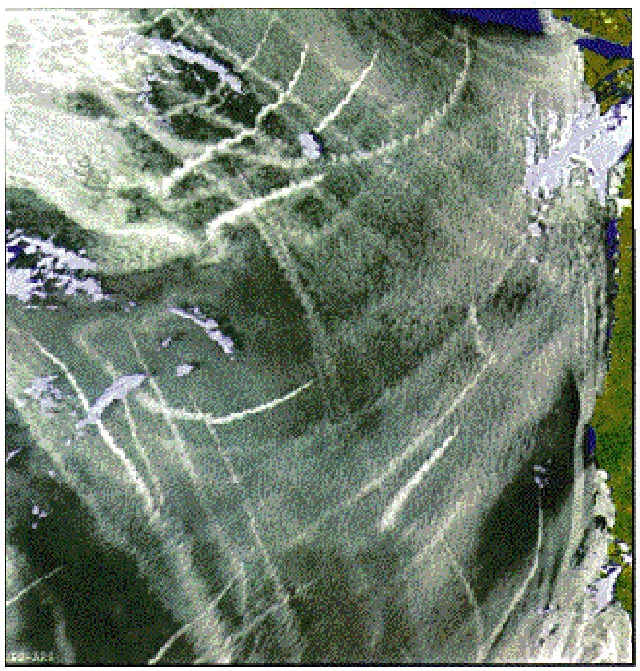
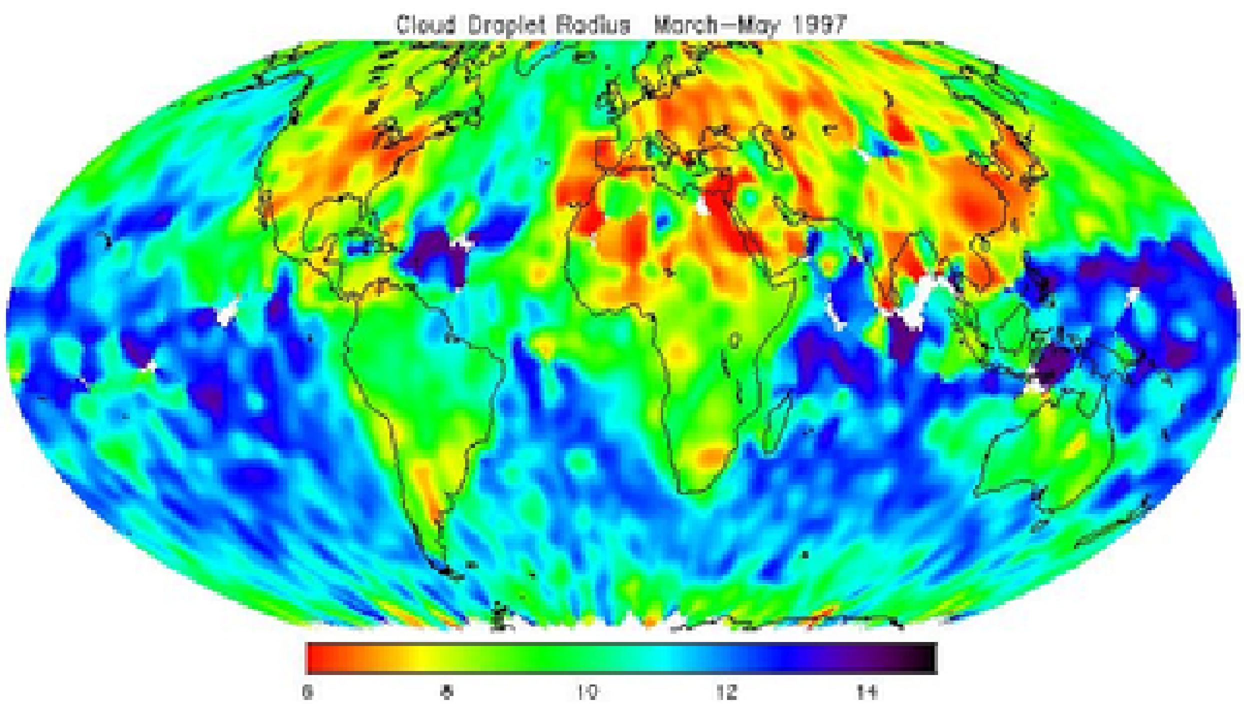


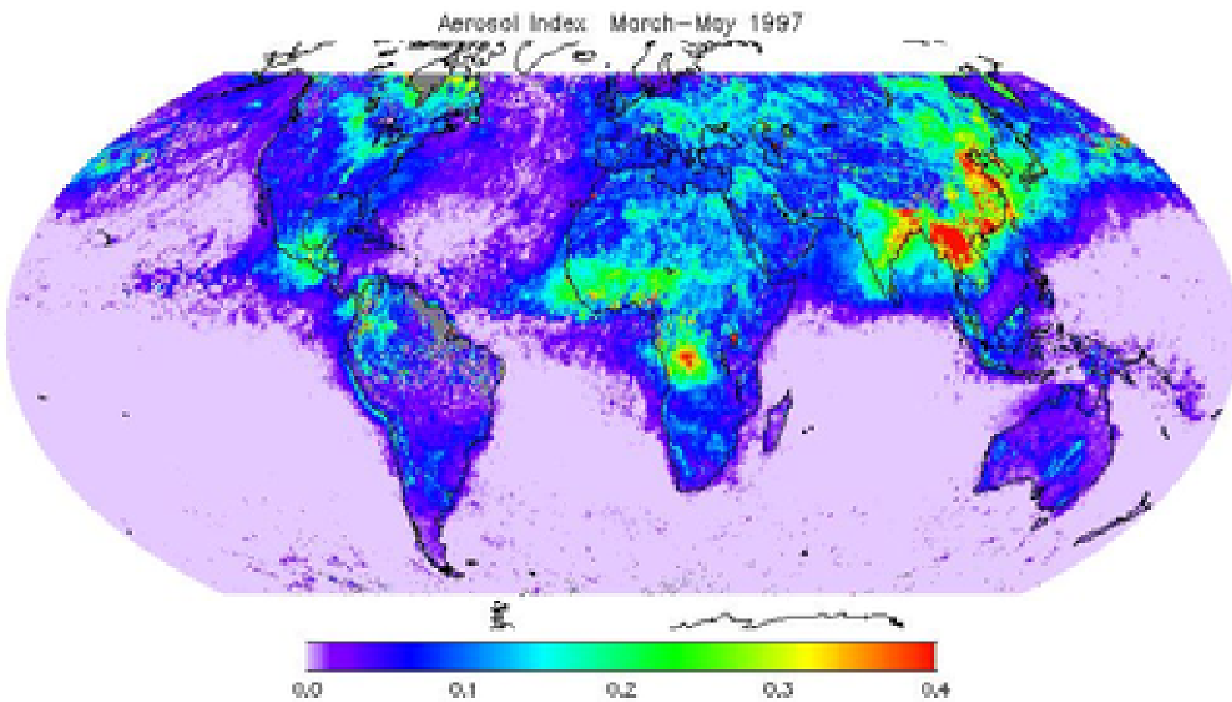
Figure 1: Ship tracks off the coast of Washington

Observational evidence: Near-global retrieval

From Bréon et al., Science 2002: Droplet effective radius



From Bréon et al., Science 2002: Aerosol Index ($\approx N_a$)



First indirect aerosol forcing from GCMs

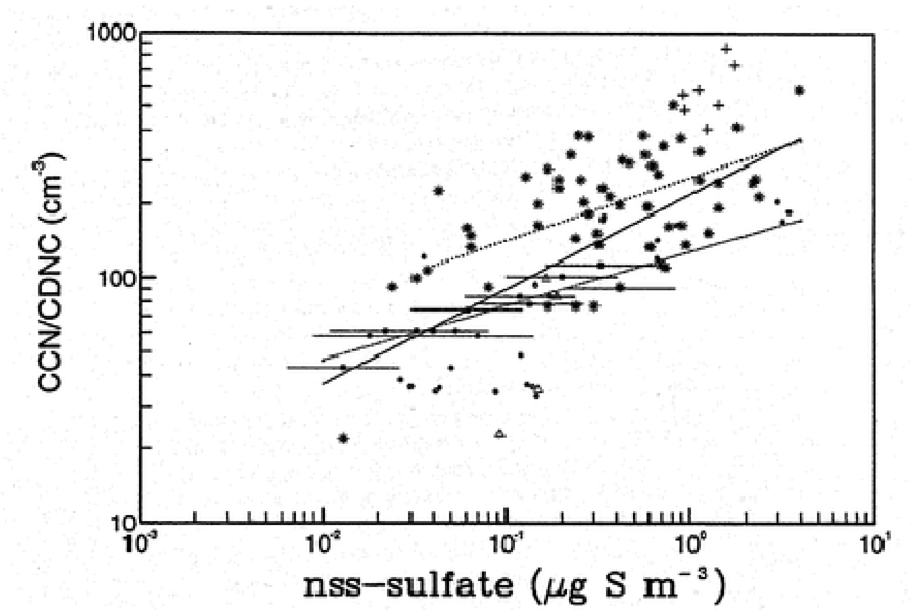
Table 5.11a: Comparison of model predicted indirect forcing without cloud amount and liquid-water path feedback.

Model	Pre-industrial aerosol (Tg)	Industrial aerosol (Tg)	N_d parametrization	Cloud cover parametrization	Forcing (Wm^{-2})
B&L (1995)	0.34 Tg S	Sulphate: 0.44 Tg S	Various empirical results	Le Treut and Li (1991); Roeckner *et al.* (1991)	−0.5 to −1.4; −0.5 to −1.5
Jones and Slingo (1996)	0.16 Tg S	Sulphate: 0.3 Tg S	Jones *et al.* (1994b); Hegg (1994); B&L (1995)	Smith (1990)	−1.5; −0.5; −0.6
Chuang *et al.* (1997)	Sulphate: 0.25 Tg S, Carbon aerosols: 1.72 Tg	Sulphate: 0.30 Tg S	Chuang and Penner (1995)	NCAR-CCM1	−0.62 to −1.24 (internal mix); −1.64 (external mix)
Feichter *et al.* (1997)	Sulphate 0.3 Tg S	Sulphate: 0.38 Tg	B&L (1995)	Sundqvist *et al.* (1989)	−0.76
Lohmann and Feichter (1997)			B&L (1995)	Sundqvist *et al.* (1989)	−1.0
Chuang *et al.* (2000)	Sea salt: 0.79Tg, Dust: 4.93 Tg, Sulphate: 0.25 TgS, Organic matter: 0.12 Tg	Sulphate: 0.30 TgS, Organic matter: 1.4 Tg, BC: 0.19 Tg	Chuang and Penner (1995)		−1.85 (all aerosols) −1.51 (all carbon aerosols) −1.16 (biomass aerosols only); −0.30 (sulphate only)
Kiehl *et al.* (2000)			Martin *et al.* (1994); Martin *et al.* (1994) with N_d minima; Jones *et al.* (1994b); B&L (1995)	Rasch and Kristjansson (1998)	−0.68; −0.40; −0.80, −1.78
Rotstayn (1999)	Sulphate: 0.21 TgS	Sulphate: 0.30 TgS	B&L (1995); Roelofs *et al.* (1998)	Smith, (1990)	−1.2; −1.7
Iversen *et al.* (2000)	Sulphate: 0.14 TgS, BC: 0.01 TgC, Sea salt and dust: included, but not quantified	Sulphate: 0.60 TgS, BC: 0.25 TgC	Similar to Chuang and Penner (1995)	Rasch and Kristjansson (1998)	−1.36

“Consensus” of global results (Penner et al., 2001)

- First (Twomey) effect only: -0.3 to -1.8 W m^{-2}.
- First and second effects: -0.65 to -4.8 W m^{-2}.
- Average for first effect ≈ 1 W m^{-2}.
- Second effect $> 50\%$ of first effect.
- Most studies only consider sulfate, but some of these implicitly include the effect of other industrial aerosols.

An empirical parameterization of droplet number N_d



Used by Boucher & Lohmann (Tellus, 1995) to express $N_d = f(SO_4^{2-})$ in a GCM.

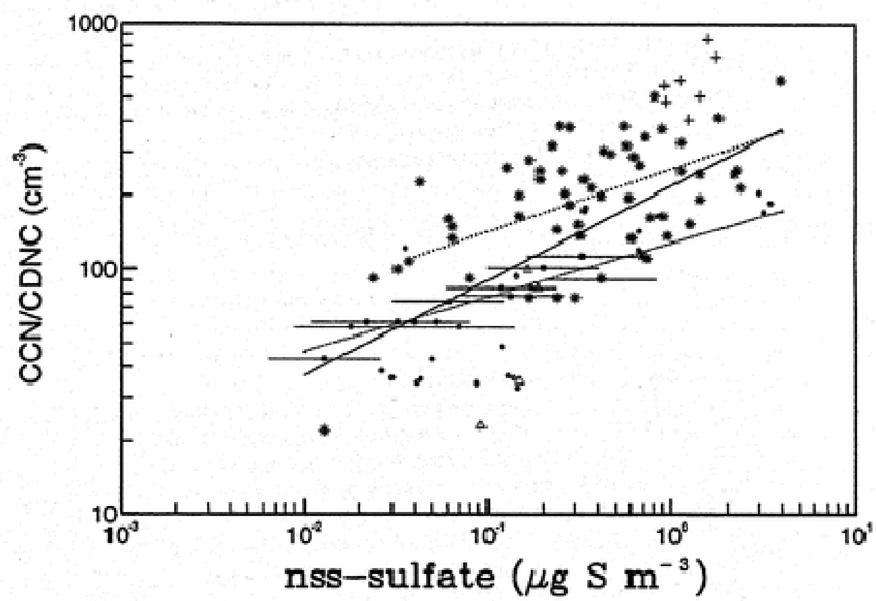
Composition specificity of indirect effect

Two studies considered effects of sulfate and carbonaceous aerosols separately:

- For first effect, Chuang et al. (2000) obtained: –1.85 (total forcing), –1.51 (all carbon aerosols), –1.16 (biomass aerosols only), –0.30 (sulfate only).
- For first and second effects, Lohmann et al. (2000a) obtained: –1.1 to –1.9 (total forcing), –0.9 (carbon only), –0.4 (sulfate only).

But both used a similar cloud-droplet parameterization, which forces the carbonaceous indirect forcing to be stronger than the sulfate indirect forcing. (Anthropogenic OC forms new particles quickly, but anthropogenic sulfate assumed to add to mass of pre-existing particles.)

Observations: Sulfate is important.



From Boucher & Rodhe (Univ. Stockholm tech report, 1994) (see also Boucher & Lohmann, Tellus, 1995)

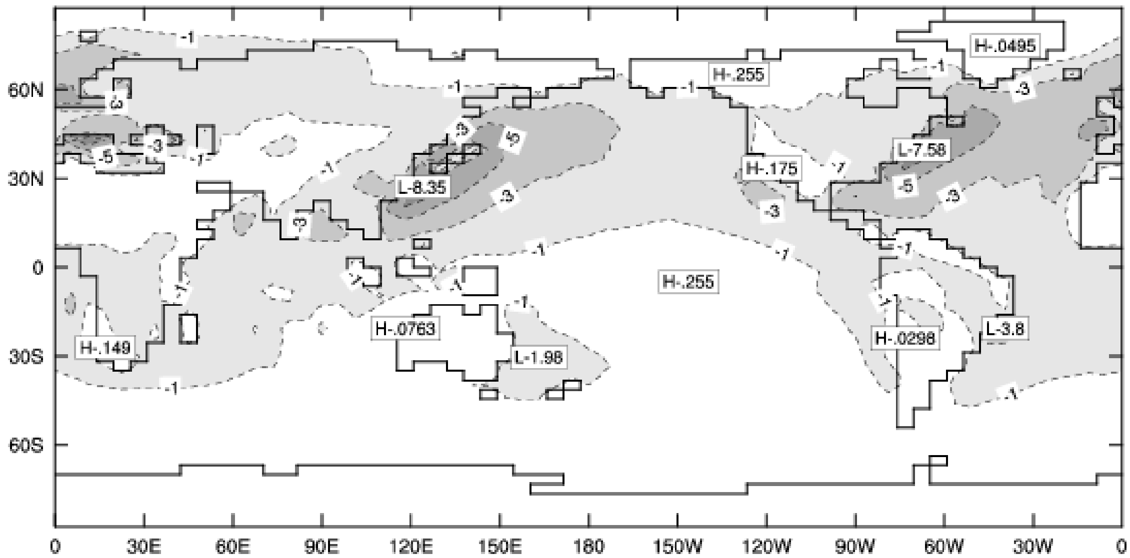
Observations: Organic carbon important too.

- Organics may be the dominant source of potential CCN in some circumstances (Novakov & Penner, Nature 1993).
- Pure organic aerosols can be intrinsically CCN active (Novakov & Corrigan, GRL, 1996)

But aerosols are usually internally mixed:

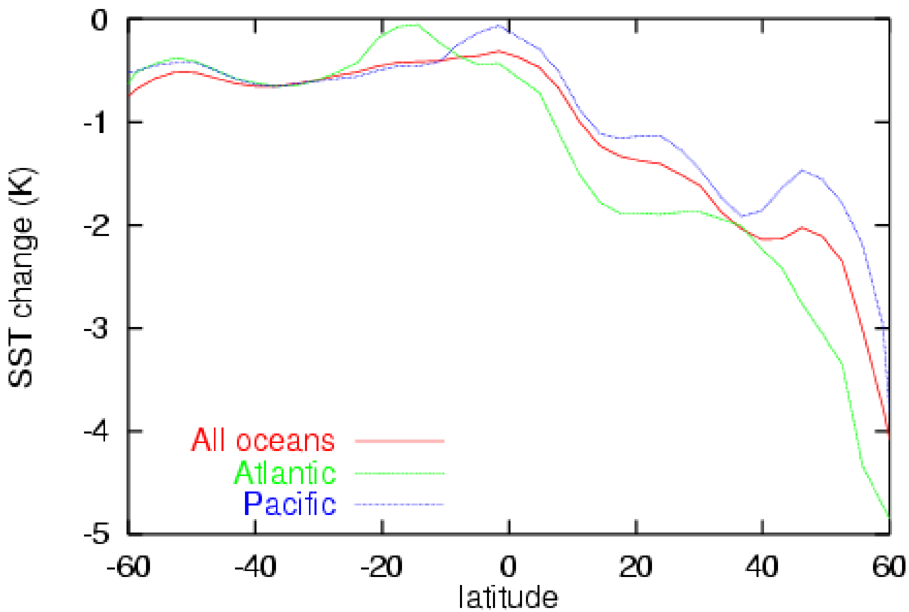
- Aerosols from biomass burning are primarily organic, but associated inorganics may enhance their CCN activity (van Dinh et al., Atmos. Res. 1994).
- Or, if the aerosol is primarily sulfate, associated organics may decrease the critical supersaturation for cloud droplet formation (Shulman et al., GRL 1996, Facchini et al., Nature 1999).

Indirect aerosol forcing varies in space



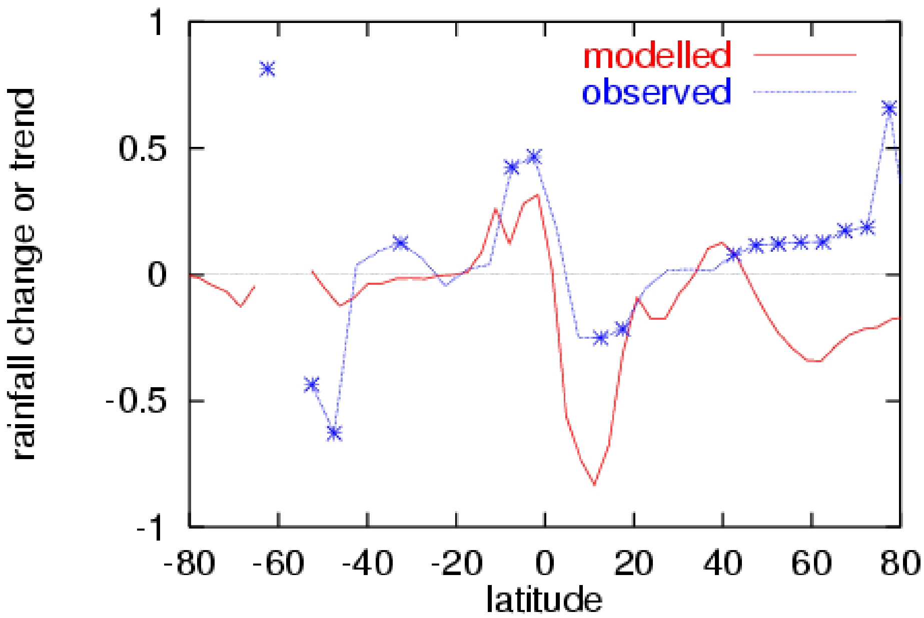
First indirect sulfate aerosol forcing from Rotstayn & Penner, J. Clim. 2001.

Equilibrium surface temperature change in an AGCM



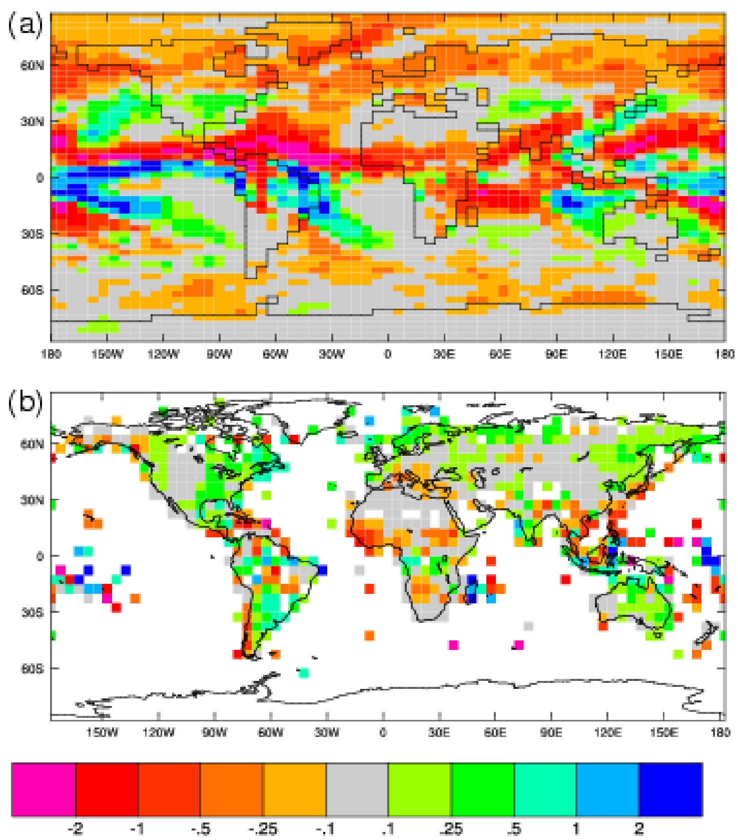
CSIRO AGCM, coupled to mixed-layer ocean: T_s response to the indirect effect of sulfate aerosol [present-day (1985) minus preindustrial].

Rainfall response to the above T_s change



Modelled change (1985 minus preindustrial) and observed 1900–1998 trend in rainfall over land (from Rotstayn & Lohmann, J. Climate, in press 2002). Asterisks denote trend significant at 5% level.

(a) Modeled rainfall change; (b) observed trend



On the extended Sahelian drought

- Strong drying trend observed from 1950 to 1985; some amelioration of drought since then.
- European and North American sulfur emissions increased strongly from 1945 to late 1970s.
- Dry Sahelian conditions associated with quasi-hemispheric SST anomaly pattern: cool in NH and warm in SH (e.g., Folland et al., Nature, 1986).
- Dynamical changes in model (in response to indirect aerosol effect) are similar to those observed in dry periods, e.g., stronger African easterly jet and weaker tropical easterly jet.

The above suggests that indirect sulfate aerosol forcing may have contributed to the extended Sahelian drought.

Indirect aerosol effect and Chinese rainfall?

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Abrupt change of the mid-summer climate in central east China by the influence of atmospheric pollution

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Author blames recent summer pattern of “north drought with south flooding” in eastern China on direct effect of sulfate aerosol (but it could be the indirect effect too!)

Summary

- Observational evidence to support (first) indirect aerosol effect is now very strong.
- Difficult to quantify composition specificity at present, but both sulfate and organic carbon appear to be important.
- Spatial variability of indirect forcing is important – crucially affects climatic response, especially in tropics.
- Possible links to Sahelian and Chinese rainfall demand further investigation.
- More observational work strongly needed, especially regarding role of different aerosol types.